A Circums ellar H_2O Maser associated with the Galactic Circ ımnuclear Molecı lar Disk?

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ABSTRACT

In the course of conducting a survey of 22-G z $_2$O masers in the inner galaxy, we discovered a naser source in Sgr A West. It is located $\sim$30″N and E of SgrA*, near the edge of the Eastern arn of he radio nini-spiral, which presumably coincides with the inside edge of the circumnuclear disk. Furthermore, the radial velocity of the maser is remarkably similar to that expected for gas in the circumnuclear disk at this location. We have also found a luminous, reddened star having a bolometric magnitude and IR spectrum characteristic of an M supergiant at this location. The extinction is consistent with a location in the inner galaxy, near or possibly within, the circumnuclear disk. If this star is associated with the circumnuclear disk, it will have implications for star formation in the unusual galactic center environment.

Subject headings: Galaxy:Center, Masers, Infrared:Stars, Stars: formation, Stars:AG 3 and Post-AGB, Stars:Supergiants

1. Introduction

Indicators of recent star formation ıear the galactic center have been noted for some ,ime. For example, RS7, a red supergiant located in the central parsec (Sellgren *et al* 1987), the relatively blue objects in the central cluster, RS16 (Tamblyn, & Rieke 993) and the presence of hot young He-emission-line stars (Krabbe *et al.* 991) have often been taken to imply an episode of star formation $\sim 10^7$ years ago. However, given the unusual conditions of the very inner galaxy, star formation is problematic. Morris (1993) has argued that tidal forces, magnetic field pressure, and large internal turbulence create conditions

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which allow cloud collapse only by external influences such as shocks or cloud-cloud collisions, and that such conditions would be likely to lead to an IMF favoring high mass stars.

H_2O masers are among the classic signatures of current star formation, although they are also found in the circumstellar shells of late-type stars. We are conducting a 22-GHz survey at the VLA of IRAS-selected H_2O maser candidates projected within ~300 parsecs of the galactic center (Levine & Morris 1994; Taylor, Morris, & Schulman 1993); one of the goals of the survey is to learn more about where star formation occurs. This project has so far led to the detection of 54 H_2O masers in the inner $4° \times 4°$, and in the course of this work, we serendipitously discovered a very interesting 22-GHz source 45" from our phase calibrator, SgrA*. The maser position is coincident with the inner edge of the galactic circumnuclear disk (CND), and the maser has been identified with a red star observed in another ongoing survey project (Figer, 1995) using the UCLA twin-channel near-IR array camera (McLean *et al.* 1993, 1994) at Lick Observatory.

The CND is a clumpy collection of clouds having a large velocity dispersion but distributed in a predominantly rotating torus centered on SgrA*. The disk is present at radii from 1.5 to 7 pc, at an inclination of 70° with the major axis at '25° East of North (Jackson *et al.* 1993). It is rotating with a circular velocity of ~110 km s^{-1}. There are large local deviations from the overall rotation at a level of ~30 km s^{-1} and even larger deviations in the western segment. The CND is generally considered to be an accretion feature. Rieke (1989) notes that the size scale of the CND is similar to that inferred for the accretion disks of Seyfert galaxies. There is evidence for inflow of gas through the disk; Jackson *et al.* (1993) find an inflow of neutral gas of about 10^3 to 10^4 $M_\odot$ in about 10^6 years into the central cavity. The fate of this gas may be star formation (Krabbe et al. 1991) or it may leave the region as a wind (e.g., Wardle & Königl 1990).

2. Observations

2.1. 22-GHz VLA Data

We used the VLA on 1993 October 4, 8, & 9 in the DnC hybrid configuration to survey IRAS-defined 22-GHz H_2O maser candidates. At 1.3 cm and low galactic latitudes, the DnC configuration produced a fairly circular synthesized beam of ~3.3″ diameter. The primary beam is ~1.5′. The uncertainty in the maser position is dominated by the uncertainty in the position of SgrA* at $17^h42^m29^s.314$, -28°59′18″.3 (1950) ~ ± 0.2″ (Rogers *et al.* 1994).

Over the course of our 15-hour run, we observed the field centered on SgrA* 23 times, in order to use the point source as a phase calibrator. Each observation consisted of 2 consecutive 90-second snapshots at overlapping frequency settings chosen such that the full velocity range of the observation was centered at +40 km s^{-1} or 40 km s^{-1}, depending upon galactic longitude, in the sense of overall rotation. The combined spectral coverage for the Sgr A* field was ±172 km s^{-1} with 5 km s^{-1} velocity resolution. The ± 98 km s^{-1} velocity range received coverage in all 23 observations.

The data were edited and calibrated in the standard way using AIPS. The SgrA* data were iteratively self-calibrated using increasingly refined CLEAN map models and the results were applied to phase calibration of the dataset. CLEAN channel maps of the SgrA* field were made as a check on the self-calibration quality; it was during inspection of these channel maps that the maser in the field was discovered. The channel map where the maser emission peaks is presented in Figure 1. The channel maps have an average rms noise of 8 mJy, allowing very significant detection of the 347 mJy maser. Variability of the maser over the 5 day period of the observations is not more than 15%.

2.2. Near-IR Observations

As part of a survey to find hot, young, emission line stars in the Galactic Center, we surveyed ~24′ x 12′ using the UCLA twin-channel infrared camera (McLean *et al.* 1993, 1994) on the Lick Observatory 3-m Shane telescope, which gives a plate scale of ~0.7″/pixel. The imaging surveys, done in 1994 June, used broadband H and K′ filters as well as narrow-band filters centered at 2.058 μm ($\lambda/\Delta\lambda$ ~100), 2.085 μm (80), 2.165 μm (100), 3.09 μm (80), and 3.15 μm (80); pairs of wavelengths are observed simultaneously.

The imaging surveys were followed by a targeted spectroscopic survey using the same setup in 1994 July. H and K spectra were obtained by inserting grisms into each beam (R_H ~ 520 and R_K ~ 540). The rectangular slit had dimensions of 1.4″ x 120″ giving critical sampling of the slit image. Additional data for the central few arcminutes, including the star identified as the counterpart to the 22-GHz maser, were obtained in mid-October, 1994, using the same equipment with "dust" (λ=3.28 μm, $\lambda/\Delta\lambda$=45) and nbL (λ=3.6 μm, $\lambda/\Delta\lambda$=45) filters.

Astrometry for the images was done by offsetting from IRS7 using the position determined by Becklin *et al.* (1987), resulting in positions good to ~0.5″. The position of the infrared counterpart coincides with the maser position to within 0.5″, and is coincident with extended H_2 and Br-γ emission (DePoy, Gatley, & McLean, 1989), associated with the eastern arm of the mini-spiral. The IR counterpart is unresolved.

Haller (1992) observed the star identified as the maser counterpart at H and K, and this star may also be associated with IRS24 or 23, although the situation is somewhat confusing. We note that there is no source in the near-1]i images within several arcseconds of the stated position of IRS23 (Lebofsky *et al.* 1982a) ($\sim 11''$ south of the maser counterpart); and that, while there is a source near the position of IRS24 ($\sim 5''$ NE of the maser counterpart), it is about an order of magnitude fainter than the maser counterpart. These circumstances are consistent with Haller's source list (1992), and we speculate that the maser counterpart may have been a source of' confusion or contamination in the literature on IRS23 and 24.

The infrared imaging survey frames were bias-subtracted, sky subtracted, flat-fielded, registered, and photometry was performed with DAOPHOT routines in IRAF using an aperture with diameter = $4.2''$ and a local sky annulus for subtracting local diffuse contributions from the unresolved light of background stars. IRS9 and IRS11 were used to calibrate the zero points at H and K (Becklin *et al.* 1978), while IRS7 and IRS3 were similarly used at nbL (Tollestrup, Capps, & Becklin 1989). It was assumed that the flux density in the nbL filter is the same as that which would be measured in a classical L filter. Measurements at K' were transformed into K magnitudes using the transformation, K=K'-0.2(H-K) as per Wainscoat *et al.* (1992). The photometry gives K=8.30, H-K=2.47, K-L=1.95, where errors are due to uncertainties in the zero-point calibrations and are likely to be less than 0.2 magnitude.

The 2-D spectra were reduced by subtracting a sky/bias/dark frame taken by nodding the telescope in the long-dimension of the slit. Dome lamps were used to produce flat images, and A-type main sequence stars were observed at a similar time and air mass to that of the maser counterpart in order to correct for atmospheric absorption. Brackett-series absorption was removed from these spectra by interpolation. The frames were calibrated in wavelength using the sky OH emission lines, then one dimensional spectra were extracted with the IRAF APEXTRACT routines, using interactively fitted apertures. The immediate lode of the maser counterpart is contaminate by H_2 and Br-γ line emission, so an additional background component had to be subtracted.

The extracted spectra were coadded for the three slit positions, corrected for atmospheric absorption, dereddened based upon the extinction derived from the photometry and the extinction law of Rieke *et al.* (1989), scaled according to a black-body fit to the atmospheric standard star, and then flux calibrated on an absolute scale by fitting the flux density to that measured during the June run. The spectra are shown in figure 2.

3. Results and Discussion

Figure 1 shows the location of the new maser source at $17^h42^m32^s.00$, -28 °.58'47'.'8 ("1950)1 near the eastern arm of the mini-spiral, with the HCN (J = 3→2) contours from Jackson *et al.* ("1993) overlaid. This position is 47.3'' (1.9 pc at 8.5 kpc) from the position of SgrA*. The maser is clearly superimposed on the CND and is, in fact, close to the position of the HCN peak. The maser has a double-peaked spectrum (Figure 3) typical of circumstellar H_2O masers (Palagi *et al.* 1993), with peaks at 45.3 and 55.8 km s^-*, implying a systemic velocity of ~50.5± ~5 km s^{-1}.

In a previous survey of this region, Lindqvist, Winnberg, & Forster (1990) conducted a single-dish search for H_2O emission around a sample of 33 OH/IR stars (Winnberg *et al.* 1985) in the inner 50 pc. They detected 22 GHz maser emission around four of the OH/IR stars, two of which were within 40'" 01 our position; while the positions of the OH/IR stars are distinct from our H_2O maser, these pointings would have put the position of our source barely within their half-power beam radius. However, they do not seem to have detected it. Both of these detected H_2O masers have spectra that are consistent with the spectra of the OH masers on which their search was targeted. The OH data give systemic velocities 01 -27 km s-^{1} (OH359.95-0.05) and 70 km s-' (OH359.953-0.041) for these OH/IR stars. OH359.95-0.05 would be unlikely to have H_2O spectral features separated from the systemic velocity by 72-83 km s^{-1}. OH359.953-0.041 could have features at the velocities where we detect emission, however, the reported H_2O spectral features are at 89.6 km s^{-1} and 55.4 km s" ^{1}, both of which are within 10 km s^{-1} of the corresponding OH feature. The derived systemic velocity from the H_2O is only about 2 km s^{-1} from the OH-derived velocity. Thus, it seems very likely that the H_2O source at OH359.953-0.041 reported by Lindqvist *et al.* (1990) is, in fact, the OH/IR star and is not the source that we have detected. At their epoch of observation, the peaks of their masers were at ~0.4 Jy to ~1.2 Jy, which our VLA observations could easily have identified. That we did not detect either of the Lindqvist *et al.* sources we attribute to the notorious variability of H_2O masers (Lewis & Engels 1991). In fact we did not detect any other 22 GHz masers within 1.5' of SgrA* to a limit of ~45 mJy near the center 01" the mapped field and ~1 Jy at the edge of the map.

If the underlying source of the H_2O maser is a spherically symmetric circumstellar shell, then the velocity at the midpoint of the two peaks should be a good tracer of the systemic velocity, though not as reliable as velocities derived from double-peaked OH maser emission from 01[/11{ stars. Relatively local sources will be moving predominantly perpendicular to the line of sight to the galactic. center, and will hence cluster around O km s^{-1}. Therefore, the derived systemic velocity of our source (50.5 km s^{-1}) implies that it is likely to be near the Galactic center. We have compared the maser velocity and position angle relative to Sgr A* (49 degrees east of north) to a very simple model of the CND a rotating torus of 1.5 2.3 pc radius with 100 km s^{-1} circular velocity having 70° inclination and major axis at 25° east of north (Jackson *et al.* 1993). The maser velocity lies on the model velocity curve at its position angle to well within uncertainties in the maser velocity. Thus, both the position and the velocity of the maser source are remarkably consistent with a location in the CND.

The reddening of the IR counterpart also implies that the source may be located in or at the edge of the CND. The star has H-K and K-L consistent with the expected colors of a late-type star given an interstellar extinction equivalent to $A_v \sim 37$ as compared to an average $A_v \sim 30$ for the Galactic Center (Becklin *et al.* 1978, Rieke *et al.* 1989). This is about the same A_v found for IRS7 from Lebofsky, Rieke, & Tokunaga (1982b) and Sellgren *et al.* (1987). We calculated the luminosity of the infrared counterpart using the following parameters for an M 5 type star: $(H-K)_0$: 0.31 and $(K-L)_0 = 0.23$ from Koornneef (1983), d=8500 pc, $A_H/A_K = 1.56$ and $A_L/A_K = 0.61$ from Rieke *et al.* (1989). The source lies very near to the reddening vector in a color-color plot, so the average extinction derived from the two color excesses was used to derive $A_K \sim 4.1$ magnitudes. These values give $M_K = -10.5$ and a luminosity of $1.0(10^5)$ $L_\odot$ assuming $BC_K = 2.8$ (Elias *et al.* 1985). This estimate is uncertain due to errors in the photometric zero points and in the assumed intrinsic colors. The luminosity is most sensitive to errors in A_K. Assuming an error of 0.1 magnitudes for all bands and intrinsic colors, the error in A_K is 0.3; and the resulting range in luminosity is $8(10^4)$ to $1.3(10^5)$ $L_\odot$.

The IR spectrum shows very deep absorption in the wings of the water absorption bands at 1.9 μm and 2.7 μm and at the CO absorption band heads between 2.3 μm and 2.4 μm. Water and CO absorption both increase with decreasing temperature, but water absorption increases with lower luminosity while CO absorption increases with higher luminosity (Baldwin, Frogel, & Persson 1973). Late-type giants, supergiants, Miras, and carbon stars all show very deep water absorption (Scargle & Strecker 1979), so the IR spectrum is best matched by a very late star. The IR counterpart has characteristics similar to IRS23, which has $M_K = -10.4$ and a spectrum with very deep water absorption (Sellgren *et al.* 1987; Lebofsky *et al.* 1982b). For IRS23, Lebofsky *et al.* assign a spectral type of M6I while Sellgren *et al.* conclude it must be later than M7III.

The high luminosity and cool temperature indicate that this star is an evolved high mass star with initial mass $\gtrsim 12$ $M_\odot$ and an age of about a few times 10^7 years (Meynet *et al.* 1994; Meynet 1994). Therefore, while not ruling out the possibility that this is merely an interesting positional coincidence, the observed properties of this source are consistent with it being a young late-type supergiant located just within the inner edge of the CND. Given this relatively short lifetime, a star would not have had time to drift into its present orbit from a distant location; if it is located within the disk, it must have formed there.

However, it need not have formed in the current manifestation of the CND; tidal, viscous, and magnetic forces, as well as collisions between clumps on a time scale much shorter than the lifetime of such a massive star, may have shredded the parent cloud and channeled the material either in toward the center or out as a wind. The time scale for one complete orbit is $\sim 10^5$ years, which is the same as the lifetime of clumps in the disk as calculated by Jackson *et al.* (1993).

If the interpretation of the maser star as a young supergiant embedded in the CND is correct, then given the factors inhibiting star formation in that chaotic environment, one must ask how it could have formed there. Two possibilities are that it formed as a result of a clump-clump collision in the CND, or as the result of a shock due to an episode of nuclear activity.

4. Conclusion

We report on the observation of a late-type supergiant having circumstellar maser emission within 2 pc of the Galactic Center. The location, reddening and systemic velocity of the source are consistent with a location in or at the edge of the circumnuclear molecular disk. Although this may be a chance coincidence, we raise the possibility that the star formed in the CND, in which case it would provide direct evidence that star formation can take place in the highly turbulent, magnetized, tidally-sheared medium of the galactic center environment.

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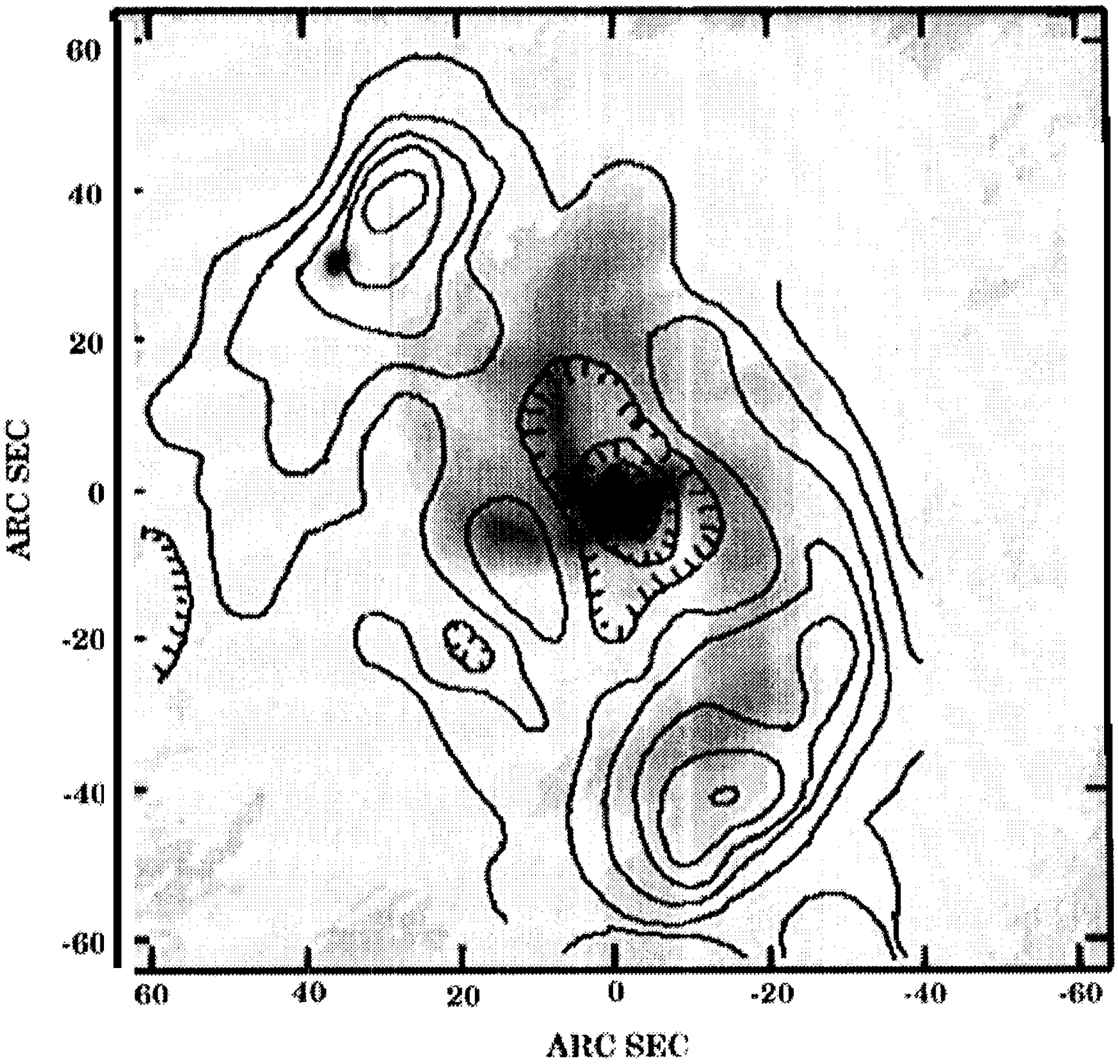

Center at RA 17 42 29.314 Dec -28 59 18.3 (B1950)
Grey scale flux range 0.000 1.5 Mega Jy/B*Hz

Fig. "1. SgrA* **field** with all data combined. Inset at the correct location is the 45.3 km s^{-1} channel map of the portion of the field containing the maser. Contours arc HCN J=3→2 emission from Jackson *et al.* (1 993)

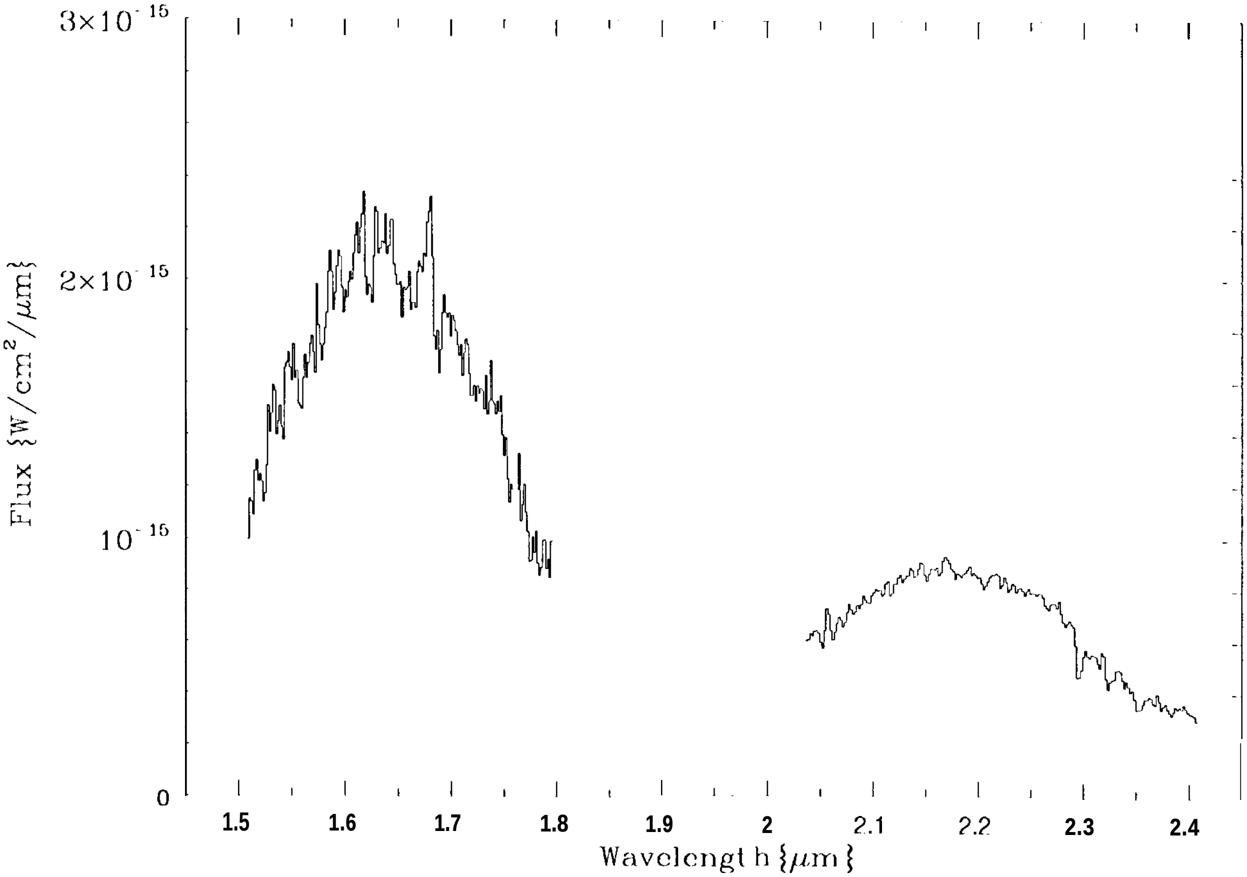

Fig. 2. Dereddened and flux calibrated H and K spectra of the IR counterpart. The feature at 2.166 μm is probably due to diffuse Br-γ emission, and features near Brackett series transitions in the H spectrum are contaminated by absorption features in the standard star. Otherwise, flux levels are accurate to within 20%.

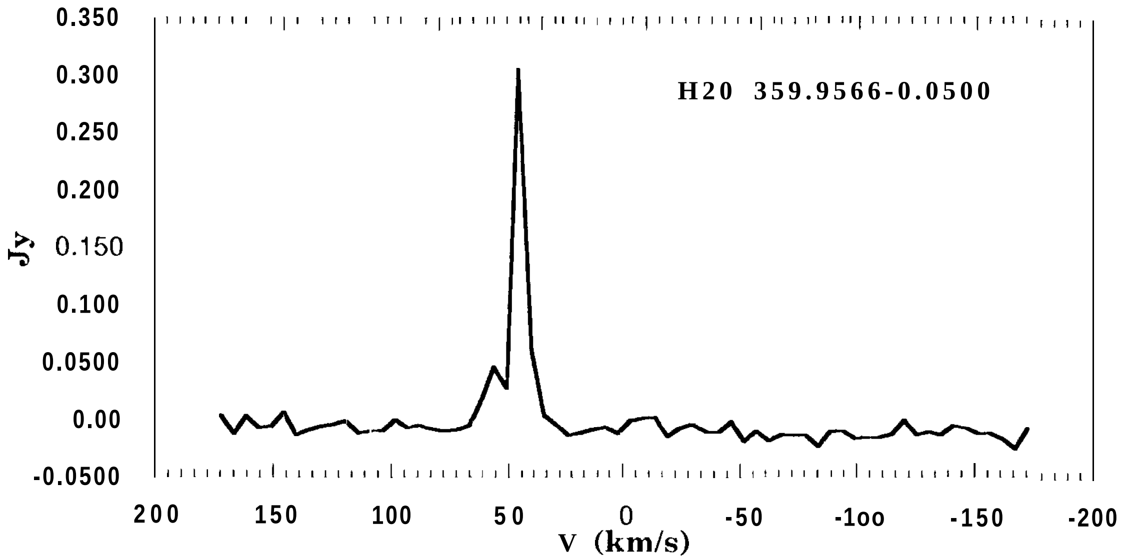

Fig. 3. The 22-GHz spectrum using the data from all 23 observations.